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A DESI DR1 Radial-Velocity Search for Dark Compact Companions: A Strong but Unconfirmed Candidate Around a dM0 Star

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ABSTRACT

We present a conservative, fully reproducible search for radial-velocity (RV) variability in the public Dark Energy Spectroscopic Instrument (DESI) Data Release 1 (DR1) Milky Way Survey (Abdul Karim et al. 2025). Using only per-epoch RV measurements, we identify stars whose velocity variability is both highly significant and robust under leave-one-out tests. A "negative space" validation pipeline then rejects ordinary luminous companions using Gaia DR3 astrometry (Gaia Collaboration et al. 2023), WISE infrared photometry (Wright et al. 2010; Mainzer et al. 2011), GALEX ultraviolet constraints (Martin et al. 2005; Morrissey et al. 2007), TESS and ZTF time-domain photometry (Ricker et al. 2015; Bellm et al. 2019; Graham et al. 2019), deep Legacy Survey imaging (Dey et al. 2019), and archival X-ray and radio catalogs.

One system, Gaia DR3 3802130935635096832 (DESI TargetID 39627745210139276), emerges as the most extreme survivor. DESI provides four RV epochs spanning 38.9 days with a maximum catalog RV span $\Delta\mathrm{RV}_{\mathrm{max}} \approx 146$ km s^{-1}. A constant-RV model is rejected at $\Delta\chi^2 \approx 2.7 \times 10^4$ (DESI-only), and the variability remains highly significant under leave-one-out tests.

A key forensic update is that Gaia DR3 resolves a neighbor at $\rho \simeq 0.69''$ with $\Delta G \simeq 2.21$ mag, implying a G-band flux ratio $b_G \simeq 0.13$ and requiring blend-aware validation. We perform blend-aware remeasurement of the DESI spectra using PHOENIX templates and physically motivated flux-ratio priors; the large RV swing persists across these remeasurements.

We then resolve the origin of previously observed arm-split pathologies by downloading per-exposure, per-camera DESI spectra (`cframe` products) and remeasuring RVs by wavelength region. Same-night exposures reveal that the full Z-arm RV is unstable when sky-dominated wavelengths (9000–9800 Å) are included, while the Ca II triplet window (8500–9000 Å) yields stable and repeatable RV behavior. Using only this empirically "trusted" window, we recover a large RV swing $\Delta\mathrm{RV} \approx 151$ km s^{-1} (from -85.6 to $+65.6$ km s^{-1}), and we find that the DESI catalog RVs for the same-night pair are biased low by ~ 25 km s^{-1} relative to the trusted-window RVs, consistent with sky-region instability affecting the catalog solution.

Finally, we verify Gaia astrometric quality metrics via a direct query to `gaiadr3.gaia_source` (script: `scripts/verify_gaia_metrics.py`), finding RUWE = 1.954 and astrometric excess noise $\epsilon_{\mathrm{AEN}} = 0.90$ mas (16.5σ significant) at $G = 17.273$. These values indicate a poor single-source astrometric fit consistent with astrometric complexity (orbital motion and/or duplicity), but are not uniquely diagnostic given the resolved neighbor. We classify Gaia DR3 3802130935635096832 as a *strong but unconfirmed* dark compact companion candidate: the RV swing persists under conservative, windowed, per-exposure analysis, but a definitive dynamical mass claim requires follow-up spectroscopy and/or high-angular-resolution imaging to separate blended components and to establish an orbit.

Keywords: Radial velocity(1332) — Compact objects(288) — M dwarfs(982) — Spectroscopy(1558)

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1. INTRODUCTION

Quiescent compact objects—white dwarfs (WDs), neutron stars (NSs), and stellar-mass black holes

(BHs)—are expected to be abundant in the Milky Way but are difficult to detect when not accreting or otherwise luminous. Radial velocities provide a purely gravitational discovery channel: a compact companion can induce large reflex motion in an ordinary star while contributing negligible light. Modern multi-epoch spectroscopic surveys are therefore natural hunting grounds for unseen companions.

DESI DR1 provides per-epoch RVs for millions of stars in the Milky Way Survey (Abdul Karim et al. 2025). While DESI was not designed as a time-domain survey, the combination of multi-epoch coverage, high spectral resolution, and uniform data processing enables a systematic search for RV outliers. In this work we:

1. define conservative RV-variability metrics that are robust to outliers;
2. scan the DESI DR1 Milky Way Survey for high-significance RV variables;
3. apply a multi-wavelength "negative space" filter that searches for *gravity without light*;
4. perform targeted orbital and forensic analyses of the strongest surviving candidate, including blend-aware remeasurement and per-exposure wavelength-region truth filtering.

All analysis scripts, configuration files, diagnostic plots, and machine-readable products are publicly available at:

`https://github.com/simulationstation/DESI-BH-CANDIDATE-SEARCH`

2. DATA SETS

2.1. *DESI DR1 Milky Way Survey*

We use per-epoch DESI DR1 Milky Way Survey RV products (Abdul Karim et al. 2025). For each epoch we extract:

- heliocentric radial velocity RV_i (km s^{-1});
- formal RV uncertainty $\sigma_{\mathrm{RV},i}$ (km s^{-1});
- modified Julian date t_i (days);
- DESI `TARGETID`;
- Gaia DR3 `SOURCE_ID` when available.

In addition, for the case-study target we download per-exposure, per-camera `cframe` spectra for the relevant exposures and remeasure RVs directly from wavelength sub-regions (Section 6.3).

2.2. *LAMOST archival spectroscopy*

We identify two public LAMOST spectra (ObsIDs 437513049 and 870813030) of the target. These spectra robustly support an early-M dwarf classification for the dominant light source. However, independent RV remeasurement of these spectra is internally inconsistent across methods (FITS-header values vs CCF refits and wavelength-split CCF), so we treat LAMOST RVs as *non-decisive* for orbit fitting and retain LAMOST primarily as a spectral-type constraint.

2.3. *Gaia DR3 astrometry and duplicity*

We verify key Gaia DR3 astrometric quality metrics via a direct `astroquery.gaia` query to `gaiadr3.gaia_source` (script: `scripts/verify_gaia_metrics.py`).

Table 1. Verified Gaia DR3 astrometric metrics for Gaia DR3 3802130935635096832.

Quantity	Value
Gaia G magnitude	17.273
Parallax ϖ (mas)	0.12 ± 0.16
RUWE	1.954
Astrometric excess noise ϵ_{AEN} (mas)	0.90
AEN significance ($\epsilon_{\mathrm{AEN}}/\sigma_\epsilon$)	16.5

An elevated RUWE (commonly RUWE $\gtrsim 1.4$) indicates a poor fit of the five-parameter single-source astrometric model and is often associated with unresolved binaries, blends, or other astrometric complexity. The parallax is poorly constrained and we therefore do not adopt a Gaia-only geometric distance.

A major forensic update is that Gaia DR3 resolves a close neighbor at a separation $\rho \simeq 0.688''$ with $\Delta G \simeq 2.21$ mag. This neighbor lies within the DESI $1.5''$ fiber aperture and must be treated as a potential blend contaminant.

2.4. *Additional surveys*

The multi-wavelength validation uses:

- WISE/2MASS photometry (Wright et al. 2010; Mainzer et al. 2011; Skrutskie et al. 2006);
- GALEX NUV constraints (Martin et al. 2005; Morrissey et al. 2007);
- TESS full-frame-image photometry (Ricker et al. 2015);

- ZTF multi-year g, r photometry (Bellm et al. 2019; Graham et al. 2019);
- Legacy Survey imaging (Dey et al. 2019);
- ROSAT/XMM/Chandra X-ray catalogs and NVSS/FIRST/VLASS radio surveys (non-detections used as upper limits).

3. RV VARIABILITY METRICS

3.1. *Single-target RV statistics*

For each target with N RV epochs we define the maximum observed RV span:

$$\Delta \mathrm{RV}_{\max} = \max_i (\mathrm{RV}_i) - \min_i (\mathrm{RV}_i). \tag{1}$$

Table 2. Definitions for Equation (1).

Symbol	Meaning
RV_i	Radial velocity at epoch i (km s^{-1})
$\Delta\mathrm{RV}_{\max}$	Maximum RV span across all epochs (km s^{-1})
$\max_i(\cdot)$	Maximum over epochs indexed by i
$\min_i(\cdot)$	Minimum over epochs indexed by i
N	Number of RV epochs
i	Epoch index

To quantify the significance of variability we define:

$$S = \frac{\Delta \mathrm{RV}_{\max}}{\sqrt{\sum_{i=1}^{N} \sigma_{\mathrm{RV},i}^2}}. \tag{2}$$

Table 3. Definitions for Equation (2).

Symbol	Meaning
S	Global RV-variability significance (dimensionless)
$\Delta\mathrm{RV}_{\max}$	Maximum RV span (km s^{-1})
$\sigma_{\mathrm{RV},i}$	RV uncertainty at epoch i (km s^{-1})
N	Number of RV epochs
i	Epoch index
$\sum_{i=1}^{N}(\cdot)$	Sum over epochs $i = 1$ to N
$\sqrt{\cdot}$	Square-root operator

3.2. *Leave-one-out robustness and leverage*

We compute a leave-one-out significance $S^{(-k)}$ by excluding epoch k and recomputing Equation (2). We then define:

$$S_{\mathrm{min,LOO}} = \min_{1 \le k \le N} S^{(-k)}, \qquad S_{\mathrm{robust}} = \min\left(S,\, S_{\mathrm{min,LOO}}\right). \tag{3}$$

Table 4. Definitions for Equation (3).

Symbol	Meaning
$S^{(-k)}$	Significance recomputed with epoch k removed (dimensionless)
k	Index of the excluded epoch (dimensionless integer)
$S_{\mathrm{min,LOO}}$	Minimum of $S^{(-k)}$ over $k = 1, \ldots, N$
S_{robust}	Conservative significance statistic used for selection
$\min(\cdot)$	Minimum operator
N	Number of RV epochs

We also define a leverage statistic:

$$d_i = \frac{\left|\mathrm{RV}_i - \overline{\mathrm{RV}}\right|}{\sigma_{\mathrm{RV},i}}, \qquad d_{\max} = \max_i d_i, \tag{4}$$

where $\overline{\mathrm{RV}}$ is the inverse-variance-weighted mean RV.

Table 5. Definitions for Equation (4).

Symbol	Meaning
d_i	Leverage of epoch i (dimensionless)
$d_{\max}$	Maximum leverage over epochs indexed by i
RV_i	RV at epoch i (km s^{-1})
$\overline{\mathrm{RV}}$	Inverse-variance-weighted mean RV (km s^{-1})
$\sigma_{\mathrm{RV},i}$	RV uncertainty at epoch i (km s^{-1})
$\lvert \cdot \rvert$	Absolute value operator
$\max_i(\cdot)$	Maximum over epochs indexed by i

4. NEGATIVE-SPACE VALIDATION PIPELINE

For each RV-variable candidate we apply a multi-wavelength filter designed to select systems with strong gravitational evidence for a companion but little corresponding light. Key checks include Gaia astrometry/duplicity (including explicit neighbor searches), WISE/GALEX constraints, TESS/ZTF photometry, deep imaging, and X-ray/radio catalog searches.

Only one object, Gaia DR3 3802130935635096832, survives all cuts and is subjected to detailed forensic validation below.

5. CASE STUDY: GAIA DR3 3802130935635096832

5.1. *DESI per-epoch RVs and extreme variability*

Table 6. DESI DR1 per-epoch catalog RV measurements for Gaia DR3 3802130935635096832.

Epoch	Source	MJD	Date (UT)	RV $\pm\sigma_{\rm RV}$ (km s^{-1})
1	DESI	59568.488	2021-12-20	-86.39 ± 0.55
2	DESI	59605.380	2022-01-26	$+59.68 \pm 0.83$
3	DESI	59607.374	2022-01-28	$+26.43 \pm 1.06$
4	DESI	59607.389	2022-01-28	$+25.16 \pm 1.11$

The maximum catalog RV span is $\Delta\mathrm{RV}_{\max} \approx 146$ km s^{-1} over 38.9 days. A constant-RV model is rejected at $\Delta\chi^2 \approx 2.7 \times 10^4$ (DESI-only).

5.2. *Blend constraint from* ΔG

The Gaia-resolved neighbor has $\Delta G \simeq 2.21$ mag. The corresponding G-band flux ratio is:

$$b_G = 10^{-0.4\Delta G}. \tag{5}$$

Table 7. Definitions for Equation (5).

Symbol	Meaning
b_G	Flux ratio in Gaia G band (neighbor/primary; dimensionless)
ΔG	Gaia G magnitude difference (mag)
$10^{(\cdot)}$	Base-10 exponential
0.4	Magnitude-to-log$_{10}$ flux conversion factor

With $\Delta G \simeq 2.21$, $b_G \simeq 0.13$. Because the neighbor is close and likely redder, the effective flux ratio can be larger in redder DESI channels.

5.3. *Why simple flux dilution cannot create a 146–151 km s^{-1} swing*

If an RV estimator behaved like a linear flux-weighted centroid of two spectra, the measured RV would be bounded by the flux-weighted average. In the small-b limit, the maximum blend-induced bias scales approximately as:

$$|\Delta\mathrm{RV}_{\rm blend}| \lesssim b\ |\mathrm{RV}_2 - \mathrm{RV}_1|, \tag{6}$$

so that even a large component separation $|\mathrm{RV}_2 - \mathrm{RV}_1| \sim 200$ km s^{-1} implies $|\Delta\mathrm{RV}_{\rm blend}| \sim 26$ km s^{-1} for $b \simeq 0.13$.

Table 8. Definitions for Equation (6).

Symbol	Meaning
$\lvert\Delta\mathrm{RV}_{\rm blend}\rvert$	Magnitude of blend-induced RV bias (km s^{-1})
b	Flux ratio (neighbor/primary; dimensionless)
RV_1	RV of the dominant-light component (km s^{-1})
RV_2	RV of the contaminating component (km s^{-1})
$\lvert\cdot\rvert$	Absolute value operator
$\lesssim$	"Less than or approximately equal to"

This bound does *not* rule out more pathological failure modes (e.g. a pipeline locking onto different components across epochs or wavelength-dependent template mismatch), motivating the blend-aware and per-exposure truth filters below.

6. FORENSIC TRUTH FILTERING: BLEND-AWARE AND WAVELENGTH-REGION RV TESTS

6.1. *Blend-aware DESI remeasurement*

We re-fit the DESI spectra using PHOENIX templates for an early-M primary and a late-M neighbor, performing χ^2 minimization with inverse-variance weights and physically motivated priors on flux ratio. Across reasonable template choices and fixed blend fractions ($b \in \{0.05, 0.13, 0.20\}$), the inferred combined-arm RV swing remains comparable to the catalog swing, indicating that the large RV excursion is not an obvious artifact of neglecting a $\sim 13\%$ contaminant.

However, model-comparison statistics (e.g. ΔBIC) can prefer two-component fits even when b is fixed to unrealistically small values. Because reduced chi-squared values remain $\chi^2_\nu \gg 1$ in many low-resolution fits, we interpret such preferences as being driven primarily by template mismatch (model misspecification), not as decisive evidence that blending explains the RV variability.

6.2. *Per-exposure, per-camera arm-discrepancy diagnosis*

Motivated by earlier arm-split pathologies in coadds, we downloaded per-exposure DESI `cframe` products for

EXPIDs 114768, 120194, 120449, and 120450. We renormalize formal uncertainties by reduced chi-squared χ^2_ν and estimate RV uncertainties using a curvature-based $\Delta\chi^2 = 1$ criterion.

Same-night exposures (120449 and 120450; 15 minutes apart) show:

- R-arm RVs are stable and consistent between exposures.
- Full Z-arm RVs are unstable, showing a $\sim$ 34 km s^{-1} discrepancy between exposures.
- Within Z, the Ca II triplet region is stable (few km s^{-1}), while the sky-dominated red end is unstable.

6.3. *Trusted-window RV curve (Ca II triplet, 8500–9000 Å)*

We define the Ca II triplet window (8500–9000 Å) as an empirically trusted window for RV inference for this target. Table 9 reports per-exposure RVs derived using only this window.

Table 9. Per-exposure RVs from the trusted window (Ca II triplet, 8500–9000 Å).

EXPID	MJD	Trusted RV	Catalog RV	Trusted − Catalog
114768	59568.488	−85.6	−86.39	+0.8
120194	59605.380	+65.6	+59.68	+5.9
120449	59607.374	+53.1	+26.43	+26.7
120450	59607.389	+50.3	+25.16	+25.1

The trusted-window RV swing is $\Delta\mathrm{RV} \approx 151.2$ km s^{-1} (from −85.6 to +65.6 km s^{-1}), consistent with (and slightly larger than) the catalog-scale swing. The same-night pair is biased low in the catalog by $\sim$ 25 km s^{-1}, consistent with the catalog solution being pulled by the unstable sky-dominated red end of the Z arm.

6.4. *Same-night residual discrepancy and systematic floor*

Although the trusted window dramatically improves stability, the same-night exposures differ by $\Delta\mathrm{RV} \approx$ 2.8 km s^{-1}. The curvature-based uncertainties for the trusted-window fits are $\lesssim 0.4$ km s^{-1} per exposure, implying formal high significance. However, reduced chi-squared values remain $\chi^2_\nu > 1$ (typically 2–7), indicating residual template mismatch and/or remaining systematics. We therefore interpret the same-night residual as evidence for a *few km s^{-1} systematic floor* in windowed DESI RVs for this blended M-dwarf target, even in the trusted window.

7. PHOTOMETRIC, INFRARED/UV, X-RAY, AND RADIO CONSTRAINTS

TESS photometry shows no deep eclipses or large coherent modulation. ZTF photometry limits large-amplitude rotational modulation, disfavoring purely activity-driven explanations for a $\sim$ 150 km s^{-1} swing. WISE colours ($W1 - W2 \simeq 0.05$) show no strong IR excess. GALEX NUV non-detection disfavors a hot WD companion. No significant X-ray or radio counterpart is found in major catalogs, consistent with a non-interacting (quiescent) system.

8. LIMITATIONS

The system remains unconfirmed due to:

1. Sparse DESI cadence (four epochs; two nearly simultaneous) and intrinsic period aliasing.
2. Confirmed close neighbor inside the fiber: blend-aware inference is mandatory.
3. Residual systematics at the few km s^{-1} level persist even in the trusted window.
4. LAMOST RVs are not decisive due to internal inconsistencies across extraction methods.
5. Gaia RUWE/AEN are elevated but are not uniquely attributable to orbital wobble given duplicity.

9. CONCLUSIONS

Gaia DR3 3802130935635096832 is an extreme DESI DR1 RV variable with a large catalog RV swing and a strong "darkness" profile (no strong IR/UV excess, no large photometric modulation, no cataloged X-ray/radio counterpart). Gaia DR3 confirms a close neighbor at $\rho \simeq 0.69''$, motivating blend-aware and wavelength-dependent validation.

Per-exposure, per-camera validation identifies the sky-dominated red end of the DESI Z arm as the source of the previously observed instability; restricting to the Ca II triplet window yields a trusted-window RV curve with a $\sim$ 151 km s^{-1} swing and explains why the catalog RVs for the same-night pair were biased low.

We therefore retain this system as a *strong but unconfirmed* dark compact companion candidate. The highest-value next step is spatially resolved, high-resolution spectroscopy and/or high-angular-resolution imaging to separate the blended components and convert the large RV swing into a definitive dynamical mass constraint.

10. DATA AND CODE AVAILABILITY (INCLUDING REQUIRED ARCHIVE DOIS)

This work used public survey and archive data. Where required by journal policy, we cite dataset DOIs for MAST-hosted and IPAC/IRSA-hosted data products.

10.1. *MAST-hosted datasets (TESS, GALEX)*

All TESS Full Frame Images used in this work are available at MAST: 10.17909/3Y7C-WA45.

All GALEX catalog constraints used in this work (GALEX/MCAT) are available at MAST: 10.17909/T9H59D.

10.2. *IPAC/IRSA-hosted datasets (WISE, 2MASS, ZTF)*

The AllWISE Source Catalog used in this work is available at IRSA: 10.26131/IRSA1.

The 2MASS All-Sky Point Source Catalog used in this work is available at IRSA: 10.26131/IRSA2.

ZTF photometric data access for this work used IRSA services associated with: 10.26131/IRSA539.

10.3. *Reproducibility*

All scripts, configuration files, diagnostic plots, and machine-readable results used in this work are publicly available at:

`https://github.com/simulationstation/DESI-BH-CANDIDATE-S`

Software: Astropy (Astropy Collaboration et al. 2013, 2018), Astroquery (Astroquery Collaboration et al. 2019), Lightkurve (Lightkurve Collaboration et al. 2018), NumPy (NumPy Developers 2020), SciPy (SciPy 1.0 Contributors et al. 2020)

Facilities: DESI, Gaia, LAMOST, TESS, GALEX, WISE, ZTF

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